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Proposal for a high brightness γ-ray source at the SXFEL*

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High brightness γ-rays produced by laser Compton scattering (LCS) are ideal probes for the study of nucleon and nuclear structure. We propose such a γ-ray source using the backscattering of a laser from the bright electron beam produced by the linac of the Shanghai Soft X-ray Free-electron Laser (SXFEL) test facility at the Shanghai Institute of Applied Physics (SINAP). The performance is optimized through theoretical analysis and benchmarked with 4D Monte-Carlo simulations. The peak brightness of the source is expected to be larger than 2×10^{22} photons/(mm^2 mrad^2 s 0.1%BW) and photon energy ranges from 3.7 MeV to 38.9 MeV. Its performance, compared to Extreme Light Infrastructure-Nuclear Physics (ELI-NP), and the Shanghai Laser-Electron Gamma-ray Source (SLEGS), is given. The potential for basic and applied research is also briefly outlined.

Keywords: High brightness γ-ray source, Laser Compton scattering (LCS), Soft X-ray Free-electron Laser (SXFEL)

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I. INTRODUCTION

Over the past decades, with remarkable advancements in the fields of high intensity lasers and high brightness electron beams, laser Compton scattering (LCS) light sources [1], based on a process in which relativistic electron beams scatter lasers to produce quasi-monochromatic X-rays or γ-rays, have found a broad range of applications. At photon energies below 100 keV, although storage ring light sources [2] and X-ray free electron lasers [3] can produce X-rays at higher brightness, LCS light sources offer attractive, complementary capabilities at a smaller fraction of the cost and size [4] for medical applications [5–9]. At γ-ray photon energies, LCS light sources will produce the highest brightness, enabling a variety of applications [10–14], including nuclear physics [10–13], nuclear astrophysics [11], polarized positron beams [15], polarized neutron beams [16], production of medical radioisotopes [17], nondestructive detection of radioactive isotopes [18], assay of nuclear materials [18], etc.

Although the Compton effect was discovered in the early 1920's by A. H. Compton as his Nobel-Prize-winning work, it was not until 1960's that a method of very high energy γ-rays via the LCS process in charged particle accelerators was proposed independently by Milburn [19], and Arutyunyan and Tumanyan [20]. While a number of successful demonstrations of the LCS concept have been made through the years, the γ-ray yield was quite low [21–23]. In 1978 the first γ-ray LCS facility, the Ladon project, was brought into operation in Frascati [24]. It was followed by several new LCS γ-ray facilities, including LEGS@NSLS[25] and HIγS@DFELL in the US [26], GRAAL@ESRF in France [27], ROKK in Russia [28], and LEPS@SPring-8 in Japan [29, 30]. Among these facilities, Ladon, LEGS, and GRAAL were decommissioned in 1993, 2006, and 2008, respectively, HIγS and LEPS are still active for low energy nuclear structures, nuclear astrophysics, and hadron physics studies. There is still growing interest in building new γ-ray facilities in storage ring light sources, e.g., LCS γ-ray sources at the TERAS [31], SAGA [32], UVSOR-II [33], LEPS2 [35], and NewSUBARU [34] in Japan. The HIγS team also proposed the HIγS2 project [36] to further increase the photon flux. Some newly built 3rd generation light source facilities are also pursuing to integrate γ-ray sources in their storage rings, e.g. PLS in Korea [37], ALBA in Spain [38], CLS in Canada [39], MAX-IV in Sweden [40], DAΦNE at LNF-INFN in Italy [41], and SSRF in China [42].

With the introduction of a photocathode radio-frequency (RF) electron gun, the linac electron beam quality has been improved dramatically during the last decades. As pointed out in Ref. [43], linac based LCS light source holds great promise for compact X-rays. There are currently many efforts all over the world for the development of such kind of X-rays, e.g. ATF at BNL [44] and PLEIADES at LLNL [45, 46] in the US, PHOENIX at HZDR in Germany [47], AIST at ETL [48], LUCX [49] and STF [50] at KEK in Japan, TTX at Tsinghua University [51] in China, and etc. For the γ-ray energies, colliding lasers with high quality electron beam from linac offers opportunities for generation of γ-rays with an exceptionally narrow spectral width ($< 0.1\%$) for photo-nuclear experiments, especially to conduct nuclear resonance fluorescence experiments [52, 53]. LLNL made an important step forward, producing a mono-energetic MeV-level γ-ray source [54, 55], enabling entirely new isotope-specific applications of importance to material science, medicine, industry, and engineering, which opens up a new era of nuclear photonics [14, 56–58]. With its great success, X-band techniques based on the MEGa-ray project [59, 60] at LLNL is under development. It is followed by the Extreme Light Infrastructure-Nuclear

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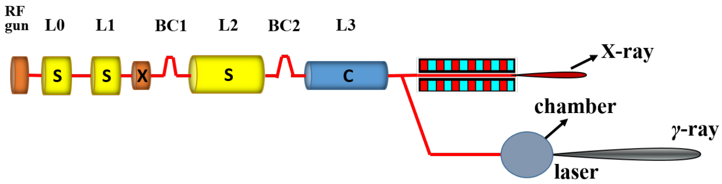

Fig. 1. (Color online) Schematic layout of the SXFEL project.

Physics (ELI-NP) project [61, 62], a major facility of the Nuclear Physics Long Range Plan in Europe [63]. ELI-NP, now under construction in Bucharest-Magurele, Romania, will be one of the three pillars of ELI and will consist of two components: a very high intensity laser beam and a very intense (10^{13} γ/s), brilliant γ beam, 0.1% bandwidth, with γ photon energy up to 19 MeV, which will create a new European laboratory with a broad range of science covering the frontier of fundamental physics, new nuclear physics and astrophysics as well as applications in diverse fields.

In this paper, we propose a high brightness, narrow bandwidth γ-ray source by using the high brightness electron beam from the linac of the Shanghai Soft X-ray Free-electron Laser (SXFEL) facility [64]. The main parameters of SXFEL will be described in Sec. II. In the following Section, the analytical optimization benchmarked with 4D Monte-Carlo simulations will be presented. Its performance will be compared to ELI-NP and the Shanghai Laser Electron Gamma Source (SLEGS). The potential opportunities offered by combining bright X-ray and γ-ray will be briefly outlined. Some concluding remarks will be given in the last section.

II. SHANGHAI SOFT X-RAY FREE-ELECTRON LASER TEST FACILITY

The SXFEL test facility is currently under construction in the SSRF campus, with the primary purpose of delivering fully coherent radiation at the wavelength of about 8.8 nm. With energy upgraded to 1.3 GeV, it is possible to push the X-ray wavelength down to the water window ($\sim$3 nm) and even the magnetic window ($\sim$1 nm). As shown in Fig. 1, this facility is based upon an electron linac, composed of a photoinjector, hybrid S-band and high gradient C-band accelerators, and 2 bunch compressors. The X-ray FEL is produced in a two-stage cascaded harmonic generation undulator system, and its performance is characterized in the X-ray transport and diagnostic system at the end. The main parameters of SXFEL is shown in Table 1.

TABLE 1. Main parameters of the SXFEL project.

Parameters	Baseline	Upgrade	Unit
e- beam energy	0.84	1.3	GeV
e- energy spread	<0.15%	<0.15%	
e- bunch charge	0.5	0.5	nC
e- normalized emittance	<1.5	<1.5	mm mrad
e- pulse length (FWHM)	<1	< 1	ps
e- beam current	500	500	A
e- repetition rate	10	10	Hz
FEL wavelength	8.8	3	nm
FEL power	>100	>100	MW
FEL pulse length	<150	<150	fs

III. PROPOSAL FOR A HIGH BRIGHTNESS γ-RAY SOURCE AT THE SXFEL

A. Basic considerations

As previously mentioned, the narrow bandwidth and high brightness γ-ray source has been long cherished by many research fields. We propose here to build a high brightness γ-ray source using the LCS mechanism based on the SXFEL linac with the energy of the electron beams ranging from 400 to 1300 MeV. As shown in Fig. 1, the γ-ray source will be located at the 2nd branch, and the colliding laser will share the same laser hutch of the seed laser of SXFEL.

We chose head-on interaction geometry to make the overlap between the electron and the laser beam larger. This source is capable to produce photon energies ranging from 3.7 MeV to 38.9 MeV of γ-rays through a Doppler up-shift of 800 nm Ti: Sapphire laser beams by a factor of $4\gamma^2E_L/(1+4\gamma^2E_L/E_e)$. In order to obtain a narrow bandwidth photon beam, we should study a variety of factors which may have impact on the γ-ray spectrum. For realistic laser-electron interactions, the laser and electron beams at the interaction point have their intrinsic divergences and energy spreads. These non-ideal factors determine the bandwidth of the scattered photon beam. The relative energy spread of the scattered photons generated by the electron beam energy spread is quite simple, $\Delta E_\gamma/E_\gamma = 2\Delta E_e/E_e$; by which the laser is natural bandwidth is the same as the laser bandwidth, $\Delta E_\gamma/E_\gamma = \Delta E_\lambda/E_\lambda$; by the intrinsic divergence of the electron beam scales as, $\Delta E_\gamma/E_\gamma = [\varepsilon_n/r_e]^2$, where ε_n and r_e are the normalized emittance and beam radius of the electron beam, respectively. The nonlinear effect associated with the laser intensity will also cause spectral broadening due to the inhomogeneous pondermotive forces during the course of the laser pulse changes in the electron's longitudinal velocity and leads to a variable redshift during scattering [65–74]. As pointed out in Ref. [71–73], even in the so-called non-relativistic regime, nonlinear effects may become significant if the pulses become relatively long. These nonlinear effects yield important spectral broadening.

In summary, for the analytical optimization of the perfor-

mance of the γ-ray source, the main goal is to maximize the on-axis spectral brightness and to reduce the bandwidth and related parameters, including the beam size, emittance of the electron beam, and the beam size, pulse duration of the laser beam. Hereafter, we assume that the pulse energy of the laser is limited to 100 mJ. The performance optimization is based on theoretical work by Hartemann *et al.* [71–73, 75] and Petrillo *et al.* [74, 76], as well as MC simulation code developed by Luo [77].

B. Performance optimization: linear and nonlinear regime

It's found [75] that in the linear regime the peak on-axis brightness is,

$$\begin{aligned}\hat{B}_x =& \frac{4\times10^{-15}}{\pi^2}\frac{\gamma_0^2}{\varepsilon^2}\frac{N_e N_\lambda}{\Delta\tau}\frac{r_0^2}{w_0^2}\frac{\eta e^{1/\mu^2}\left[\Phi(1/\eta)-1\right]-\mu e^{1/\mu^2}\left[\Phi(1/\mu)-1\right]}{\mu^2-\eta^2}\\ &\cdot\exp\left[\frac{\chi-1}{2\chi\Delta u_\perp^2}\left(2+\frac{\delta\omega^2+\delta\gamma^2\chi^2}{2\chi(\chi-1)\Delta u_\perp^2}\right)\right]\left[1-\Phi\left(\frac{\chi-1}{\sqrt{\delta\omega^2+\delta\gamma^2\chi^2}}\left[1+\frac{\delta\omega^2+\delta\gamma^2\chi^2}{2\chi(\chi-1)\Delta u_\perp^2}\right]\right)\right],\end{aligned} \tag{1}$$

where $N_e = q/e$ is the number of electrons in the bunch, $\Delta\tau$ is the bunch duration, ε is the normalized emittance, γ_0 is beam energy, and $\delta\gamma$ is the energy spread. $N_\lambda = W/(\hbar\omega_0)$ is the total number of photons in the laser pulses, w_0 is the $1/e$ focal radius, $r_0 = 2.82\times10^{-15}$ m is the classical electron radius, and $\Phi(x) = (2/\sqrt{\pi})\int_0^x e^{-t^2}\mathrm{d}t$ is the error function. $\mu = c\Delta t/2\sqrt{2}z_0$ is the normalized inverse Rayleigh length and $\eta = \varepsilon/(\gamma_0 r_b^2)c\Delta t/2\sqrt{2}$ is the normalized inverse beta function, where r_b is the radius at the focus of electron beam, Δt is the laser pulse duration, and $z_0 = \pi w_0^2/\lambda_0$ is the Rayleigh length. $\chi = \omega_x/4\gamma_0^2\omega_0$ is the normalized upshifted frequency and $\delta\omega = \Delta\omega/\omega_0$ is the relative spectral width of laser pulse.

In the nonlinear regime, when spectral broadening induced by the inhomogeneous laser pondermotive force during the interaction is considered, the brightness reads,

$$\begin{aligned}\hat{B}_x =& \frac{4\times10^{-15}}{\pi^3}\frac{\gamma_0^2}{\varepsilon^2}\frac{N_e N_\lambda}{\Delta\tau}\frac{r_0^2}{w_0^2}\int_{-\infty}^{\infty}\frac{e^{-\bar{z}^2}d\bar{z}}{(1+\eta^2\bar{z}^2)(1+\mu^2\bar{z}^2)}\exp\left[\frac{\chi\rho(\bar{z})-1}{2\chi\rho(\bar{z})\Delta u_\perp^2}\left(2+\frac{\delta\omega^2+\delta\gamma^2\chi^2\rho^2(\bar{z})}{2\chi\rho(\bar{z})(\chi\rho(\bar{z})-1)\Delta u_\perp^2}\right)\right]\\ &\cdot\left[1-\Phi\left(\frac{\chi\rho(\bar{z})-1}{\sqrt{\delta\omega^2+\delta\gamma^2\chi^2\rho^2(\bar{z})}}\left[1+\frac{\delta\omega^2+\delta\gamma^2\chi^2\rho^2(\bar{z})}{2\chi\rho(\bar{z})(\chi\rho(\bar{z})-1)\Delta u_\perp^2}\right]\right)\right],\end{aligned} \tag{2}$$

where $\rho(\bar{z}) = 1 + A_0^2 e^{-\bar{z}}/2(1+\mu^2\bar{z}^2)$, with A_0 being the maximum laser normalized vector potential.

At a given beam emittance, while tight focal size of the electron beam will cause a significant broadening of the spectrum, loosening the spot size can produce a narrower spectrum, but will decrease the overall spectral brightness of the source due to reduced electron density. It's therefore an optimum beam size for the highest γ-ray beam brightness that can be found. With the normalized emittance equal to 1.5 mm mrad (see Table 1), Figure 2 shows the peak spectral brightness for four different values of the electron beam focal radius: 5, 15, 20 and 25 µm. The spectral broadening due to a large divergence for a small beam size is clearly shown. Figure 3 shows the peak spectral brightness as a function of the electron beam focal radius with/without the nonlinear spectral broadening effect. One can see that the brightness variation as the electron beam size is not very sensitive, since it depends on the combined effects of divergence induced spectral broadening and the laser-e beam overlap integral. In order to achieve narrower bandwidth, we prefer to use a relatively large electron beam size, as shown in Fig. 2. Therefore, 20 µm is chosen as the working value of the e-beam size.

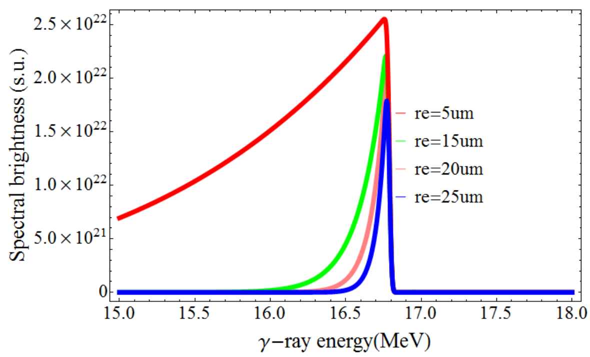

Fig. 2. (Color online) Peak spectral on axis brightness for different electron beam sizes.

As the scaling laws (Eq. (1) and Eq. (2)) suggest, the peak spectral brightness of LCS light sources is proportional

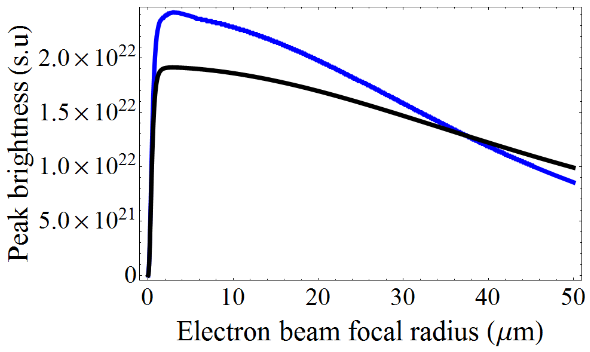

Fig. 3. (Color online) Peak brightness as a function of the electron beam focal radius (blue: linear, black: nonlinear).

to the electron beam brightness. For a fixed beam size, large emittance means large divergence, and the divergence-induced spectrum broadening decrease the peak brightness rapidly. Moreover, reducing the beam emittance to around 0.5 mm mrad, the peak brightness would be increased by a factor of $\sim$3.

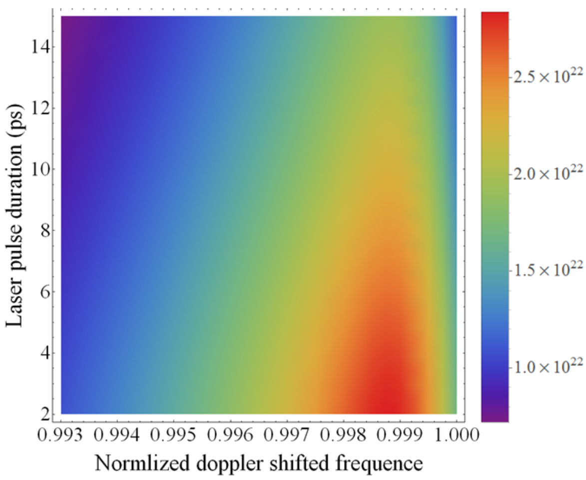

Fig. 4. (Color online) Peak spectral on-axis brightness as a function of the normalized Doppler-shifted frequency. χ, and laser pulse duration, Δt.

In the case of Fourier-transform-limited laser pulses, the relation between the pulse duration, Δt, and the spectral bandwidth, $\Delta\omega$, satisfies: $\Delta\omega\Delta t = \sqrt{2}$. For large values of the laser pulse duration, the laser bandwidth is narrow, and the normalized vector potential is small, which allows for minimal linear and nonlinear spectral broadening. However, the overlap integral becomes small as the normalized parameters, η and μ, become large. Conversely, for ultrashort laser pulses, the fractional laser bandwidth contributes strongly to the spectral bandwidth, and nonlinear effects become important, further degrading the brightness. Peak spectral on-axis brightness as a function of the normalized Doppler-shifted frequency, χ, and laser pulse duration, Δt, are shown in Fig. 4 (nonlinear effect ignored) and Fig. 5 (nonlinear effect included). When nonlinear effects are neglected, a relatively large range of laser pulse durations yield high-brightness operations; the limits are set by the laser bandwidth for short pulses, which broaden the x-ray spectrum by diffraction for long pulses. Accounting for nonlinear effects, however, reveals a much tighter constraint on the drive laser pulse duration, as shown in Fig. 5, where the strength of the ponderomotive force is also indicated: the optimum lies in the range of 3–7 ps, and a duration of 5 ps would be a good working point.

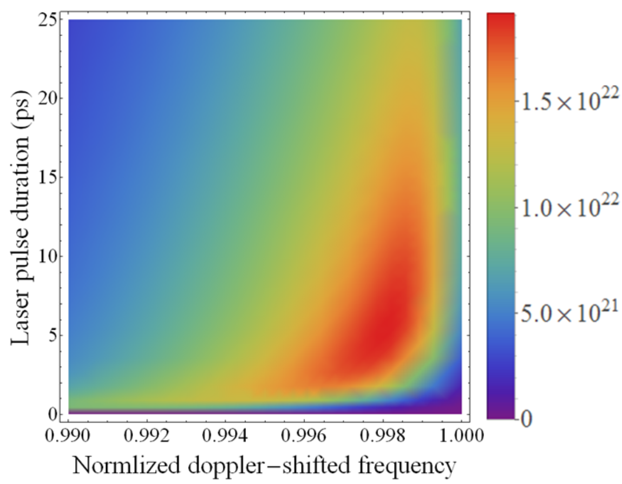

Fig. 5. (Color online) Peak spectral on-axis brightness as a function of the normalized Doppler-shifted frequency. χ, and laser pulse duration, Δt. (Nonlinear effect included)

The size of the laser beams also have an impact on the laser normalized vector potential. The larger the laser beam size, the smaller the laser normalized vector potential, accordingly to reduce the nonlinear-induced spectral broadening. However, the larger the laser beam size, the smaller the laser photons density, and thus smaller photon flux and smaller the spectral brightness. Meanwhile, the Rayleigh length should be longer than the pulse duration. Small sizes will also introduce a large divergence. Figure 6 shows the peak spectral brightness as a function of the laser beam focal radius. We chose a laser spot size of 15 μm as the working point.

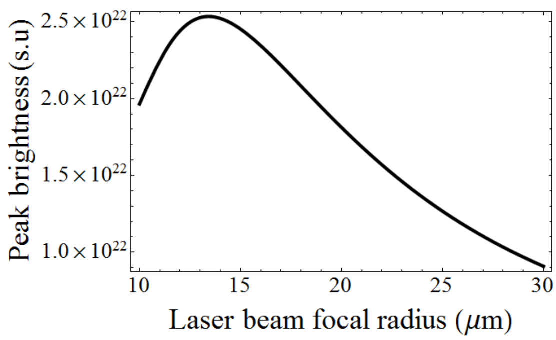

Fig. 6. Peak spectral brightness as a function of the laser focal spot size.

Through theoretical analysis, the optimized parameters of the electron beams and laser beams are finalized. To verify the predicted performance, numerical simulation is highly desirable. In SINAP, a four-dimensional (three-dimensional time and frequency-domain) Monte Carlo LCS simulation code, MCLCSS [77], has been developed with the Geant4 toolkit [78]. The code has the capability to calculate the spatial, spectral, and temporal characteristics of the LCS light sources with slanting collision configuration. The code has been benchmarked with the popular code, CAINS [79], and with realistic measurements by PLEIADES at LLNL, HIγS at Duke University and the UVSOR-II facility. As shown in Fig. 7, the simulation results agree reasonably well with theoretical predictions. A γ ray source with flux as high as 7×10^7 photons/s can be achieved with the optimized parameters of the electron and laser beam at the SXFEL project.

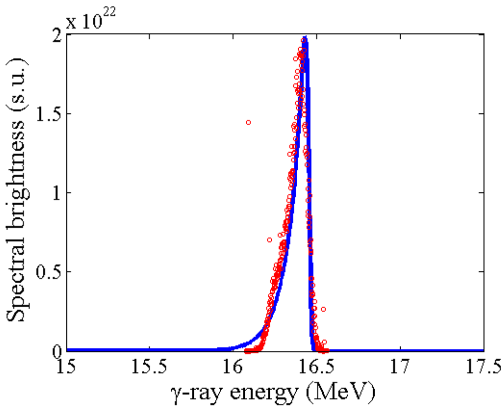

Fig. 7. (Color online) The peak spectral brightness of the γ-ray source at the SXFEL. (theory: blue line, MC simulation: red dots)

C. Comparison with ELI-NP and SLEGS

The SLEGS project [42, 80] is a LCS γ-ray source proposed at the storage ring of the SSRF. The SLEGS will be built at one of the long straight sections. There are two operational modes, intermediate energy mode with backscattering geometry, and low energy mode with side-scattering geometry. In the low energy mode, the interaction angle of the electron beam with the CO_2 incident laser can be changed continuously with a rotating platform, thus γ-ray photons with an energy ranging from 0.4 to 20 MeV. The main parameters of the low energy mode of operation of SLEGS are listed in Table 2. Similarly, the optimized performance is shown in Fig. 8.

The performance comparison of ELI-NP and SLEGS is summarized in Table 3. Despite of the lower repetition rate, single bunch operation mode with around 3 order of magnitude lower spectral density, the flux per shot and peak brightness are comparable with ELI-NP, and are 2 orders of magnitude and 11 orders of magnitude higher than that of the SLEGS project, respectively.

TABLE 2. Main parameters of the SLEGS project.

Parameters	Value	Unit
e- beam energy, E_e	3.5	GeV
e- energy spread, σ_{E_e}/E_e	0.944e-3	
e- beam current, I	300	mA
e- bunch charge, Q	0.864	nC
Bunch number	500	
e- emittance, $\varepsilon_x/\varepsilon_y$	2.59/2.59e-2	nm rad
e- beam size, σ_x/σ_y	276.9/12.24	µm
e- pulse length σ_z	3	mm
Laser wavelength, λ	10.64	µm
Laser Power, P	100	W
Laser spot size, σ_x/σ_y	50/50	µm

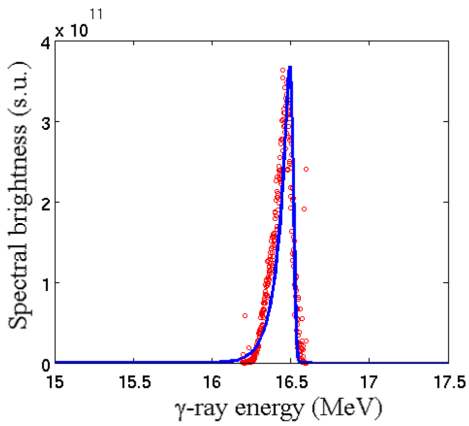

Fig. 8. (Color online) The peak spectral brightness of low energy mode of SLEGS. (theory: blue line, MC simulation: red dots)

D. Potential scientific opportunities

As aforementioned, the proposed γ-ray source at the SXFEL will be useful in diverse fields from nuclear structure physics [81–83] to nuclear isomers [84], nuclear astrophysics [85], and nuclear data [86], to space radiation effects research of aerospace electronic components, and accurate calibration of gamma detectors for aerospace. Moreover, by combining high brightness X-rays and γ-rays in a single facility, a number of opportunities for fundamental physics studies can be expected. For more than 30 years, photon colliders [87] have been considered as a natural additions to electron-positron collider projects in the high energy physics community. There has been renewed interest in recent years [88, 89] to build a photon collider as a Higgs factory, since the discovery of the Higgs boson in 2012. A new class of photon collider is proposed [90] , in which a gamma-ray beam is fired into the high-temperature radiation field of a laser-heated hohlraum. In the SXFEL case, it fits quite well and provides more precise tools for the study of the Breit-Wheeler pair production process, which is the most striking prediction of quantum electrodynamics.

The possibility of creating a nuclear gamma-ray laser (NGL) has been attracting attention for half a century [91, 92]. However, as of now, convincing data about

TABLE 3. Performance comparison

Parameters	LCS@SXFEL	ELI-NP [62]	SLEGS	Unit
Photon energy	3.7–38.9	0.2–19.5	1.47–21	MeV
Spectral density	4–39	$0.8–4 \times 10^4$	0.008–0.015	ph/(s eV)
Bandwidth	$< 0.5\%$	$< 0.5\%$	$< 0.5\%$	
Photons/shot within FWHM BW	$< 4.54 \times 10^6$	$< 2.6 \times 10^5$	< 0.00043	photons/pulse
Photons/sec within FWHM BW	$< 4.54 \times 10^7$	$< 8.3 \times 10^8$	$< 1.5 \times 10^5$	photons/second
Source size (rms)	12	10–30	$275/12\ (x/y)$	µm
Source divergence (rms)	0.8	0.03-0.2	0.6-0.9	mrad
Peak brightness	4×10^{21}–5×10^{22}	10^{20}–10^{23}	10^{11}–10^{14}	s.u.
Pulse length (rms)	0.86	0.7–1.5	10.5	ps
Repetition rate	10	100	347×10^6	Hz

its experimental solution is still absent. The key conflict inherent in the NGL concepts is the antagonism between the necessity to accumulate a sufficient amount of excited nuclei and the requirement to narrow down the emission line to its natural radiative width. For the combined high brightness narrow bandwidth X/γ sources at SXFEL, it's possible to test the X-ray pumped NGL concept [93].

IV. CONCLUSION

In this paper, the design of a narrow bandwidth, high peak brightness LCS γ-ray source based on the SXFEL linac, is presented. Its peak brightness will be larger than 2×10^{22} photons/(mm^2 mrad^2 s 0.1%BW) and photon energy ranges from 3.7 MeV to 38.9 MeV, which will enable a broad range of nuclear physics studies and advanced nuclear photonics applications. The photon flux will be at least 2 orders of magnitude, and peak brightness will be 11 orders of magnitude higher than that of the SLEGS projects. Its performance is also comparable with the most advanced γ-ray source, ELI-NP. By combing the brightness γ-rays with bright X-rays, a new type of photon collider for fundamental QED physics studies can be envisioned and the exploration of a new approach to γ-ray laser can be carried out.

It's also worthy to point out that current design studies are preliminary. There is still a lot of room for further improvement. To name a few, reduction of the emittance of the electron beam, adoption of the multi-bunch operation and the integration of the laser cavity [94], and the usage of plasma channels [95] may further increase the photon flux by orders of magnitude. Spectral broadening effects can be compensated by chirped electron beams [96], and/or suitable frequency modulation of incident laser pulses [97–99]. During the simultaneous operation of the X-ray FEL and the γ-ray source, the X/γ-ray optics demanded by the aforementioned experiments will be technically challenging. These concerns will be the topics of our future studies.

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